Developments in Mineral Deposit Modeling

JAMES D. BLISS, Editor

U.S. GEOLOGICAL SURVEY BULLETIN 2004

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1992

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Developments in mineral deposits modeling / James D. Bliss, editor.
p. cm. — (U.S. Geological Survey bulletin ; 2004)
Includes bibliographical references.
Supt. of Docs. no. : I 19.3:2004
1. Ore deposits. 2. Mines and mineral resources. I. Bliss,
James D. II. Series.
QE75.B9 no. 2004 557.3 S—dc20 91–40084
[TN263] [622'1] CIP

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Introduction and Overview of Mineral Deposit Modeling

By Dan L. Mosier and James D. Bliss

INTRODUCTION

Activities in mineral deposit modeling have continued to develop on several fronts since the publication of "Mineral Deposit Models," edited by Cox and Singer (1986). That bulletin is a collection of 87 descriptive deposit models and 60 grade and tonnage models prepared by many authors both from within and outside of the U.S. Geological Survey. The present bulletin continues that effort with the addition of new or revised models. Before these models are introduced, a review of modeling as used here is provided as well as an overview of mineral deposit modeling since the publication of Cox and Singer (1986).

EXPLANATION OF DESCRIPTIVE AND GRADE AND TONNAGE MODELS

A general definition of a mineral deposit model as found in Cox and Singer (1986, p. 2) is "the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits. The model may be empirical (descriptive), in which instance the various attributes are recognized as essential even though their relationships are unknown; or it may be theoretical (genetic), in which instance the attributes are interrelated through some fundamental concept."

With a descriptive model in hand, member deposits can be recognized and their size and grades can be used to develop a grade and tonnage model. Ideally, the data should be the estimated premining tonnages and grades. Estimates should be for the tonnage at the lowest cutoff grades. The grade and tonnage model is presented in a graphical format in order to make it easy to display the data and to compare this type of deposit with other deposit types (Cox and Singer, 1986). The plots (figs. 2-19, 21, 22, 25-34) show either grade or tonnage on the horizontal axis, whereas the vertical axis is always the cumulative proportion of deposits. The units are all metric, and a logarithmic scale is used for tonnage and most grades. Each dot represents an individual deposit, and the deposits are cumulated in ascending grade or tonnage. Owing to limitations in the plot routine, a point will not be shown on the plot if it has exactly the same value as the vertical axis (for example, the Keystone-Union deposit is not displayed in figure 12). On rare occasions, values less than the value of the vertical axis are not shown as well (for example, Hog Ranch is not displayed in figure 16). Smoothed curves, representing percentiles of a lognormal distribution that has the same mean and standard deviation as the observed data, are plotted through the points. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distributions are constructed.

OVERVIEW OF PAPERS ON DEPOSIT MODELING

A number of papers on deposit modeling and support data have been published in various places since 1986. These papers focus on descriptive deposit models and (or) grade and tonnage models that are useful for resource assessments. Some of the papers document the models originally published in Cox and Singer (1986), others attempt to improve the models' applicability in resource assessments, and still others present new deposit models. The following overview is presented chronologically by type of study. Model numbers shown in parentheses follow the format used in Cox and Singer (1986), with some modifications.

Several papers not cited in Cox and Singer (1986) document the data used in some of the grade and tonnage models. Orris (1985) provided data for 93 bedded barite deposits (No. 31b), of which less than 30 had grade and tonnage information. Additional tabulated data for each deposit include volume of deposit, associated minerals, host formation, host age, host lithology, and references. Orris and Bliss (1985) provided data for 330 gold placers (No. 39a). The data for each deposit include placer type, mining method(s), production history, bedrock source, and

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Manuscript approved for publication, July 25, 1991.

references. Bagby and Berger (1986) presented data for 31 of the deposits used in the grade and tonnage model for carbonate-hosted Au-Ag (No. 26a) and discussed the geologic characteristics of the deposit type, which (in order to accommodate the noncarbonate host rocks) they called the sediment-hosted, disseminated precious-metal deposits. A number of tables provide information on host rocks, igneous rocks, structure, mineralization age, alteration, ore bodies (form, mineralogy, gold or silver site, veins), trace-element geochemistry, tonnage, grades, and references for selected deposits. Also included are plots of trace-element variations, sulfur isotopic variation in sulfides and barite, gold grade versus tonnage, and cumulative frequency distributions of tonnages and grades. Bliss and Jones (1988) provided data for 357 deposits used to develop the grade and tonnage model for low-sulfide Au-quartz veins (No. 36a). Tabulated data for each deposit include tonnage, grades, mineralogy, and references. This paper also evaluated the frequency of occurrence, order of abundance, and assemblages of ore minerals, and displayed the results in tables and pie diagrams.

Grade and tonnage models can provide insight into geologic processes. A paper by Mosier and others (1986) documented three types of epithermal gold-quartz-adularia deposits, based on the types of basement rocks underlying the host volcanic pile. The Sado type (No. 25d) occurs over an igneous-dominant basement, the Comstock type (No. 25c) over a sedimentary-dominant basement, and the Creede type (No. 25b) over a saline-carbonate-dominant basement. Each type has different tonnages and grades, particularly among the base metals. These models indicate that basement rocks probably influence the character of the ore fluids. Grade and tonnage models are shown for the three deposit types. Tabulated data for each district include tonnage, grades, basement rocks, and references. A study by Page and others (1986) examined the platinum-group element values of 250 deposits used in the grade and tonnage model for minor podiform chromite deposits (No. 8a) to test for homogeneity of platinum-group elements within the deposit type. Analysis of variance of platinum-group element content demonstrated that deposits within terranes were not significantly different. Relatively small but significant differences in the combined medians for Ir, Ru, Rh, and Pt exist (at the 1 percent level) among terranes, but the reasons for these differences are not clear. Also, it was discovered that the platinum-group element abundances of minor podiform chromite deposits are similar to those of major podiform chromite deposits (No. 8b). A part of the analysis of platinum-group elements is tabulated, and grade models for individual platinum-group elements are shown.

There are three new descriptive deposit models based on one or two examples. These new models have not been included in this bulletin because they do not have associated grade and tonnage models. Cox and Rytuba (1987) developed a descriptive model for Lihir Island gold (No. 25), a gold deposit occurring in the root of a volcanic center. This deposit, in Papua New Guinea, is the only known example of its type. Tosdal and Smith (1987) developed two descriptive models for deposits in regionally metamorphosed eugeosynclinal rocks. (The model numbers assigned to these models should have been 36 rather than 37, in that they are not hosted in metasedimentary rocks.) First, the gneiss-hosted gold model (No. 37c) is based on the Tumco mine group and American Girl-Padre y Madre mines in the Cargo Muchaco Mountains, southeastern California. This deposit type either occurs in lenticular bodies of biotite-magnetite-quartz gneiss of volcanic or granitic origin, subparallel to the gneissic foliation, or is associated with low-angle ductile shear zones. Second, the gneiss-hosted epithermal gold model (37d) is based on the Mesquite mine, southern California, which occurs in breccia fillings, fracture fillings, and high-angle veins that cut subhorizontal amphibolite-facies metavolcanic gneiss and plutonic gneiss. The Mesquite deposit is similar to epithermal quartz-adularia-gold vein deposits (Sado type?), except that it is hosted in metaigneous rocks-this raises the question of whether or not it should be treated as another type of deposit.

Attempts to distinguish subtypes within existing deposit models have been carried out in several papers. Heald and others (1987) successfully distinguished two types of volcanic-hosted epithermal precious- and base-metal deposits through a detailed examination of the characteristics of 17 well-documented districts. These characteristics include the ore, gangue, and alteration mineral assemblages; the spatial and temporal distributions of mineral assemblages; the host-rock composition; the age relations between ore deposition and emplacement of the host rock; the size of the district; the temperatures of mineral deposition; the chemical composition and origin of the fluids; the paleodepth estimates; and the regional geologic setting. Differences in many of these characteristics were documented in the two major types designated the acid-sulfate type and the adularia-sericite type. It was found that the two most important factors for distinguishing these types are (1) the vein and alteration mineral assemblages and (2) the age relations between ore deposition and emplacement of the host rock. Bliss and others (1987) examined gold grades and volumes to distinguish among gold placer types but found that they could not distinguish most types of gold placers, except for the alluvial-plain and fan placers. However, when these data were coupled with mining methods, estimates could be made of the amount of gold remaining when a placer mine changes from small-volume mining (such as panning, sluicing, or drift mining) to large-volume mining (such as dredging or hydraulic mining). New descriptive and grade and tonnage models for two subtypes of Au-bearing skarn deposits were designated Au skarn and byproduct Au skarn (Orris and others, 1987; Theodore and others, 1990). Although the two subtypes do not differ in geologic characteristics or tonnages, there are significant differences in the median gold and silver grades. Tabulated data which are largely overlapping can be found in both Orris and others (1987) and Theodore and others (1990). Data tables give name, location (mining district), formation age/name, igneous rocks, age, ore minerals, gangue minerals, ore control, tonnage, gold grade, silver grade, base metal grades, comments and references. Cox and Singer (1988) examined the distribution of gold in three types of porphyry copper deposits designated as porphyry copper-gold (No. 20c), porphyry copper-gold-molybdenum (No. 17), and porphyry copper-molybdenum (No. 21a). This paper defines the three types of porphyry copper deposit models used in Cox and Singer (1986). It was concluded that gold content alone could not define porphyry copper-gold systems, but that the three types differed significantly in Cu-MO-AU content, magnetite content, deposit morphology, depth of emplacement, and tonnage. Mosier and Page (1988) distinguished among four subtypes of volcanogenic manganese deposits (No. 24c) based on tectonic environments. These subtypes are supported by differences in tonnage, grades, volume, lithology, mineralogy, and deposit morphology. The new models—called Franciscan (No. 24c.1), Cuban (No. 24c.2), Olympic Peninsula (No. 24c.3), and Cyprus (No. 24c.4)—each have individual descriptive and grade and tonnage models and mineral-deposit density values.

Berger and Singer (1987) developed a new grade and tonnage model for hot-spring gold-silver deposits (No. 25a) based on 10 deposits in Nevada and California.

The importance of industrial minerals in economic development has been long recognized in national and international assessments and commonly far exceeds that of fuels and metals. However, they usually receive only a passing reference. This is because, in part, they cannot always be modeled using standard grade-tonnage models. Orris and Bliss (1989) took a step in resolving this impasse by formally defining three new model types for describing industrial mineral deposits. These include (1) the contained-material model applicable to commodities where the material must meet a minimum level of purity (for example, feldspars, travertine); (2) the impurity model for commodities where the distribution of impurities affects utilization (for example, iron or aluminum in glass sand); and (3) the deposit-specific model applicable to commodities that are unique (for example, the distribution of the proportion of gem-quality diamonds, and the average diamond size in diamond kimberlite pipes). Descriptive models of 22 industrial mineral deposit types prepared by 13 contributors can be found in a report edited by Orris and Bliss (1991). Sutphin and Bliss (1990) compared amorphous and disseminated deposit types using graphite grade, tonnage, and contained carbon. While differences are clearly present in the carbon grade and tonnage between the two types, this was not the case for contained carbon.

A graphic method was develop by Bliss and others (1990) to show how tonnage data can be used to guide in the selection among the 71 deposit types (with grade and tonnage models) during the search for deposits amenable to small-scale mining. McKelvey and Bliss (1991) compared the contained copper, lead, zinc, gold, and (or) silver of a median deposit for all deposit types having grade and tonnage models with the 1989 world production of copper, lead, zinc, gold, and silver. This work shows the importance of porphyry deposit types as a source of most of these metals.

NEW DEVELOPMENTS IN DEPOSIT MODELING

This volume will be one of several pertaining to developments in deposit modeling. Future volumes will include studies on predictive resource assessments, exploration modeling, and spatial modeling. Here, we present six new descriptive models, nine new or revised grade and tonnage models, and a numerical method of matching mineral deposits to deposit models. New descriptive models were developed for thorium-rare-earth veins (No. lld), distal disseminated Ag-Au (No. 19c), solution-collapse breccia pipe uranium deposits (No. 32e), oolitic ironstones (No. 34f), laterite-saprolite Au (No. 38g), and detachment-fault base and precious metals (No. 40a). New grade and tonnage models include thorium-rare-earth veins (No. lld), distal disseminated Ag-Au (No. 19c), Sierran kuroko (28a. 1), solution-collapse breccia pipe uranium deposits (No. 32e), oolitic ironstones (No. 34f), Chugach-type low-sulfide Au-quartz veins (36a.1), and laterite-saprolite Au (No. 38g). Revised existing grade and tonnage models include hot-spring Au-Ag (No. 25a) and sediment-hosted Au (No. 26a). The principal use of grade and tonnage models is for making quantitative mineral resource assessments. A recent example can be found in a paper by Reed and others (1989) for the Seward Peninsula, Alaska. They used grade and tonnage models for Sn skarns (Menzie and Reed, 1986a), replacement Sn (Menzie and Reed, 1986b), Sn veins (Menzie and Reed, 1986c), and Sn greisen (Menzie and Reed, 1986d). These models, together with estimates of the number of undiscovered deposits, allow computer simulations to be made that estimate the amount of Sn in undiscovered deposits of the Seward Peninsula.

A new development by R.B. McCammon is the numerical characterization of deposit models. This method can be used to assign the appropriate deposit type to a target mineral deposit, permitting a quantitative matching of the description of a mineral deposit to one or more descriptive models. To facilitate the scoring used to do this, worksheets are provided for each of the descriptive models found in Cox and Singer (1986).

The descriptive model of thorium-rare-earth veins (No. lld), by Mortimer Staatz, is based on data from North American deposits. The grade and tonnage model of thorium-rare-earth veins by J.D. Bliss is different from those developed for most other deposit types modeled to date in that none of the thorium-rare-earth deposits have been mined extensively. Instead of using grades and tonnages from production plus reserves plus resources, the model is based on estimates of size of unworked veins and the median values of rock analyses. The grade and tonnage model is based on 28 deposits in the United States and one in Mexico.

The descriptive model of distal disseminated Ag-Au (No. 19c) by D.P. Cox, was developed during the analysis of Nevada's resources project for deposits that (1) are richer in Ag relative to Au, (2) contain Zn, Pb, Cu, and Mn, (3) occur near igneous intrusions, and (4) are distally associated with skarns and polymetallic veins and replacements. Some of these deposits were formerly classified as carbonate-hosted Au-Ag deposits (No. 26a; Berger, 1986a). The grade and tonnage model, by D.P. Cox and D.A. Singer, is based on data for 10 deposits from the United States, Mexico, and Peru.

The grade and tonnage model of hot-spring Au-Ag (No. 25a), by B.R. Berger and D.A. Singer, is a revision of an earlier model by Berger and Singer (1987). It is in response to the availability of grade and tonnage data for more deposits and of revised data for others.

The grade and tonnage model of sediment-hosted Au (No. 26a), by D.L. Mosier, D.A. Singer, W.C. Bagby, and W.D. Menzie, is a revision of an earlier model by Bagby and others (1986). It is in response to the availability of grade and tonnage data for more deposits and to a new definition for a deposit, which combined or separated some deposits. The result of this new descriptive definition is that some deposits included in the earlier model have been reassigned to distal disseminated Ag-Au (No. 19c) by D.P. Cox.

The grade and tonnage model of Sierran kuroko deposits (No. 28a.1), by D.A. Singer, was developed because Triassic or Jurassic deposits of the kuroko massive sulfide (No. 28a) in North America and, perhaps, South America are significantly smaller than the worldwide kuroko group as described by Singer and Mosier (1986).

The descriptive model of solution-collapse breccia pipe uranium deposits (No. 32e), by W.I. Finch, is based on deposits from the Colorado Plateau of Arizona. This deposit type is most likely an important future source of uranium. The grade and tonnage model, by W.I. Finch, C.T. Pierson, and H.B. Sutphin, is developed from data on eight deposits in Arizona. The model is atypical in that the deposit tonnages have a very narrow range and the lognormal distribution was rejected. This is also true for uranium oxide grades.

The descriptive model of oolitic ironstones (No. 34f), by J.B. Maynard and F.B. Van Houton, is an important addition to the two existing descriptive models for iron deposits including Superior Fe (Cannon, 1986b) and Algoma Fe (Cannon, 1986a). The grade and tonnage model of oolitic ironstones, by G.J. Orris, is based on 40 deposits from North and South America, Europe, and China.

The grade and tonnage model of Chugach-type low-sulfide Au-quartz veins (No. 36a.1), by J.D. Bliss, was developed because low-sulfide Au-quartz veins in and adjacent to the Chugach National Forest, Alaska, are significantly smaller and have lower Au grades than the low-sulfide Au-quartz veins (No. 36a) elsewhere in the world (modeled by Bliss, 1986). This model and the previous one developed for kuroko massive sulfide exemplify the flexibility of grade and tonnage models in conforming to a specific geologic criterion that is observed but for which the reasons are not yet clear. These and other identified subtypes represent opportunities to identify either economic and (or) geologic factors causing these differences.

Au placers have been classified using various criteria, including types and modes of transport. Placers are identified as "alluvial" when concentration has occurred in streams and rivers, "colluvial" when Au has been transported with surface material by downhill creep away from the bedrock source, and "eluvial" when a deposit develops in situ over or adjacent to the bedrock sources (Boyle, 1979). The descriptive model of laterite-saprolite Au (No. 38g), by G.E. McKelvey, is of the latter type, but it is a type that develops primarily from chemical rather than physical processes. Because these deposits develop chemically, they have been classified here as a residual rather than a depositional type of deposit. This continuum between the two types is an enigma in classification schemes and should really be represented by both types-hence its inclusion in parentheses in the depositional type of deposit (see app. A). Au is transported in water under near-surface temperature and pressure conditions, and deposition appears to be controlled by ground-water levels in areas that have or have had tropical and subtropical climate conditions. The ubiquitous nature and the hydrogeologic and paleoclimatic constraints of this deposit type could affect the applicability of the model (depending, of course, on the level of information available) in resource assessments. The deposits used in the grade and tonnage model of laterite-saprolite Au, by J.D. Bliss, are based on the model (No. 38g) by G.E. McKelvey. The grade and tonnage model is developed from data on nine, some which are poorly defined, deposits from Guyana, Western Australia, and Surname. Like the thorium-rare-earth model (No. 11d), these deposits have yet to be worked extensively.

The preliminary descriptive model of detachment-fault-related polymetallic deposits (No. 40a), by K.R. Long, is part of the continued effort to effectively describe this emerging deposit type(s). The model is preceded by a paper giving an evaluation of available descriptive and grade-tonnage data, including a list of distinguishing characteristics of detachment-fault-related mineralization. Also given is a list of deposit types commonly confused with detachment-fault-related mineralization. The descriptive model of gold on flat faults (No. 37b) by Bouley (1986) is an earlier model for this deposit type. An important revision of this model, using lithologic-tectonic environment criteria of Cox and Singer (1986, table 1), is its reclassification into the new categories of “Regional Geologic Structures” and “Extended Terranes” (see app. A).

Each of the grade and tonnage models presented in this bulletin is accompanied by a list of the deposits, locations, and, in some cases, the grade and tonnage data. The location is shown by an abbreviated form that identifies either the country or the country plus a state or province. A list of abbreviations is provided in appendix B.

Descriptive and grade and tonnage models are useful in mineral resource assessments, but, as demonstrated in these studies, they may have wider applications. Not only do these models help to define the many deposit types present, but they also help to decipher the complexities of mineral concentrations and provide insight on the genetic or geologic processes responsible for their formation.

DESCRIPTIVE MODEL OF THORIUM-RARE-EARTH VEINS

By Mortimer H. Staatz

BRIEF DESCRIPTION

SYNONYM: Rare-earth-thorium veins.

DESCRIPTION: Various thorium and rare-earth minerals in a quartz-potassium feldspar-iron-oxide gangue in veins 1 to about 1,330 m long and less than 1 cm to about 16 m thick.

TYPICAL DEPOSITS: Last Chance vein, Lemhi Pass district, Montana (Staatz, 1979); Little Johnnie vein, Powderhorn district, Colorado (Olson and Wallace, 1956); vein no. 12, southern Bear Lodge Mountains, Wyoming (Staatz, 1983); Wet Mountains area, Colorado (Armbrustmacher, 1988).

RELATIVE IMPORTANCE: A future thorium resource. Highest grade thorium resource in the United States, second largest total resource of thorium (Staatz and others, 1979). Rare earths important byproduct in some deposits; in others, the principal product.

COMMODITIES: Th, rare earths (mainly light rare earths, but at Laughlin Peak, New Mexico, the heavy rare earths most important).

OTHER COMMODITIES: None.

ASSOCIATED DEPOSIT TYPES (*suspected to be genetically related): Disseminated rare-earth minerals in both massive carbonatites and carbonatite dikes; example: one of the world's largest rare-earth deposits in a massive carbonatite at Mountain Pass, California (Olson and others, 1954).

REGIONAL GEOLOGIC ATTRIBUTES

TECTONOSTRATIGRAPHIC SETTING: Commonly associated with diverse suites of alkaline rocks and carbonatites. Thorium-rare-earth veins generally occur in an outer ring around alkaline rocks (fig. 1). May be as far as 16 km beyond outer limits of the alkaline rocks. Veins most common in the eastern part of the Cordilleran belt associated with continental crustal rocks (Staatz and Armbrustmacher, 1982).

REGIONAL DEPOSITIONAL ENVIRONMENT: Veins formed along fractures in brittle rocks. Vein fluids commonly traveled many kilometers before deposition. In a few areas, such as the Powderhorn district (Olson and Hedlund, 1981), all related igneous rocks are exposed. From the center, igneous alkaline rock complex surrounds a massive carbonatite and is bordered by fenite. Carbonatite dikes intrude outer part of alkaline rocks and neighboring country rock. Thorium-rare-earth veins intruded into an outer zone (fig. 1).

AGE RANGE: Host rock for veins: mainly Precambrian, but in several areas is Cretaceous and Tertiary. Veins: in Powderhorn and Wet Mountain districts, Colorado, formed between very late Precambrian to Ordovician (Olson and others, 1977); in Lemhi Pass district, Idaho and Montana (Staatz, 1972), Bear Lodge Mountains, Wyoming (Staatz, 1983), and Laughlin Peak area, New Mexico (Staatz, 1985), formed in Tertiary.

LOCAL GEOLOGIC ATTRIBUTES

HOST ROCKS: Hard brittle rocks. Rocks include Precambrian quartzite, hornblende schist, gneiss, granite; Upper Cretaceous Dakota Sandstone; Tertiary trachyte, phonolite, and intrusive breccia.

ASSOCIATED ROCKS: Alkalic rocks, carbonatites, fenites.

ORE MINERALOGY: principal ore minerals in most deposits: thorite±monazite. Associated minerals: ±brockite±allanite±bastnaesite. Exceptions: (1) Bear Lodge Mountains, Wyoming, no thorite, principally monazite±brockite±bastnaesite; (2) Laughlin Peak area, New Mexico, neither thorite nor monazite, principally either (a) brockite + xenotime or (b) thorium- and rare-earth-bearing crandallite.

GANGUE MINERALS: Principal minerals: quartz+iron oxides (goethite and (or) hematite)±potassium feldspar. Minor minerals: ±barite±apatite±magnetite ±rutile±anatase±zircon (Staatz, 1974).

STRUCTURE and ZONING: Veins usually fine grained and commonly heavily stained with iron oxides±manganese oxides. Mineral zoning unknown.

ORE CONTROLS: Large alkaline rock body or bodies, whose magma was source of vein fluids within about 20 km of veins (Staatz, 1974). Joints and small faults that served both as conduits for ore fluids and as sites of deposition.

ISOTOPIC SIGNATURES: Unknown.

FLUID INCLUSIONS: Unknown.

STRUCTURAL SETTING: All ore in tabular veins.

ORE DEPOSIT GEOMETRY: Veins of potential economic interest range in length from about 60 to about 1,330 m and in thickness from about 0.3 to about 16 m. Veins may strike in almost any direction. Dips of all veins steep.

ALTERATION: Iron minerals, where present, altered to goethite±lepidocrocite±hematite. Clay minerals not common; thorite often metamict, sometimes narrow zone of fenitization around vein.

EFFECT OF WEATHERING: Probably aided in forming iron-oxide minerals.

EFFECT OF METAMORPHISM: Not applicable.

GEOCHEMICAL SIGNATURES: Some enrichment of Th and rare earths in alkaline igneous rocks. Th tends to disperse rapidly in stream sediments short distances below veins (Staatz and others, 1971). Heavy metals in stream sediments not diagnostic.

GEOPHYSICAL SIGNATURES: Radiation due to thorium used to locate most veins. Generally located by hand-held geiger counter or scintillometer. Most veins too narrow and (or) poorly exposed to locate with airborne radiation counters.

OTHER EXPLORATION GUIDES: Unknown.

OVERBURDEN: Most known veins have some part exposed at surface. Veins have been traced from original exposure under as much as 10 m of overburden.

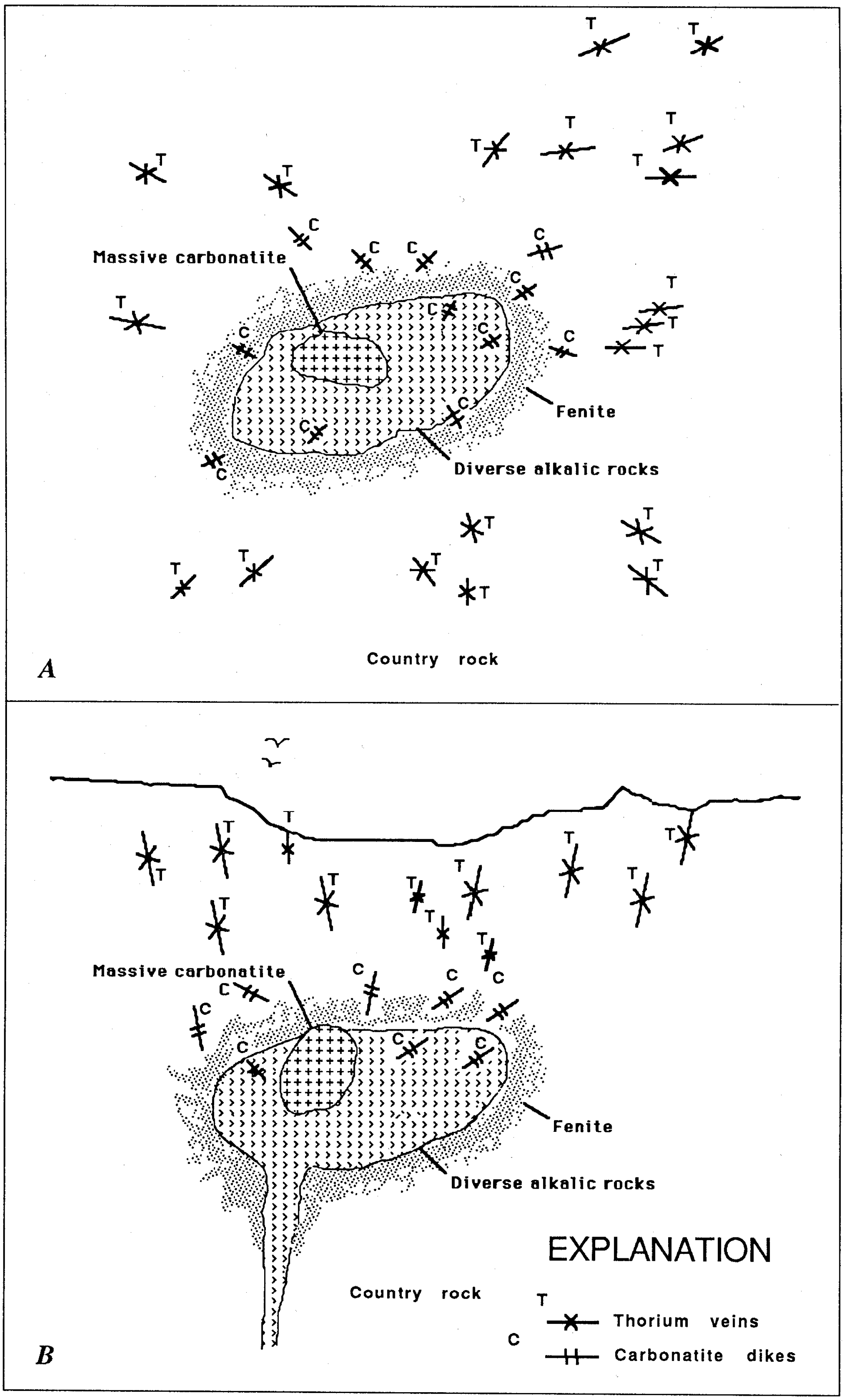

Figure 1. Idealized model showing relationship of thorium-rare-earth veins to alkalic rocks and carbonatites. *A*, Plan view. *B*, Cross-section view.

GRADE AND TONNAGE MODEL OF THORIUM-RARE-EARTH VEINS

By James D. Bliss

COMMENTS Definition of deposits for thorium-rare-earth veins used for this model is subject to several types of complications. Definition of vein-type deposits is never an easy task, since veins and mines exhibit various types of spatial relationships. Reports about thorium-rare-earth veins also show veins and mines using different scales. Some of the veins have been worked by small-scale mining. The majority of the veins are unmined. Production data are usually not available. Data on reserves, if known, are also not available. Production grades are not known. In some cases the distinction between carbonatite veins and thorium-rare-earth veins is unclear, and thus the model may contain carbonatite veins in error. To develop a model, several rules were established: (1) grades were estimated using the median values reported from samples taken from the veins; (2) when possible, veins were treated as a single deposit if they occurred within 1 km of each other; and (3) tonnage was estimated using median vein widths, lengths, and depths (depths estimated as 2.5 times length). Rules were applied when possible; in some cases, deposits were not used, since the rules could not be clearly applied. Thorium-rare-earth veins in the Powderhorn and Mountain Pass districts were considered, but data were found inadequate for estimation of grades and tonnages for veins using the stated rules. Some districts with closely spaced veins are treated as a single deposit. The model is probably biased in ways undefined, since none of the data are from deposits worked to exhaustion. See appendix B for locality abbreviations. See introduction for explanation of the grade and tonnage model as shown in figures 2–4.

DEPOSITS		DEPOSITS	
Name	Country	Name	Country
Apex	USID	I&L	USAK
Beardsley	USCO	Last Chance	USMT
Beaverhead	USMT	Lone Star No. 2	USID
Black Bear No. 2	USID	Lucky Horseshoe	USID
Black Bull No. 3	USID	Nellie B	USID
Black Rock	USMT	Paystreak	USAK
Black Rock	USID	Quartzite	USAZ
Buffalo	USID	Reactor	USMT
Cage No. 12	USID	Schwarz Ranch	USCO
Capitan Mountain	USNM	Silver Queen 38A	USID
Contact	USID	Silver Queen 52B	USID
Cottonwood	USAZ	ThO2	USID
Deer Fraction 1A	USID	Tuttle Ranch	USCO
Elkhorn	USMT	Unnamed property	MXCO
General Ike	USCO	Wonder	USID
Haputa Ranch	USCO	Wonder No. 18-Little Dandy	USID

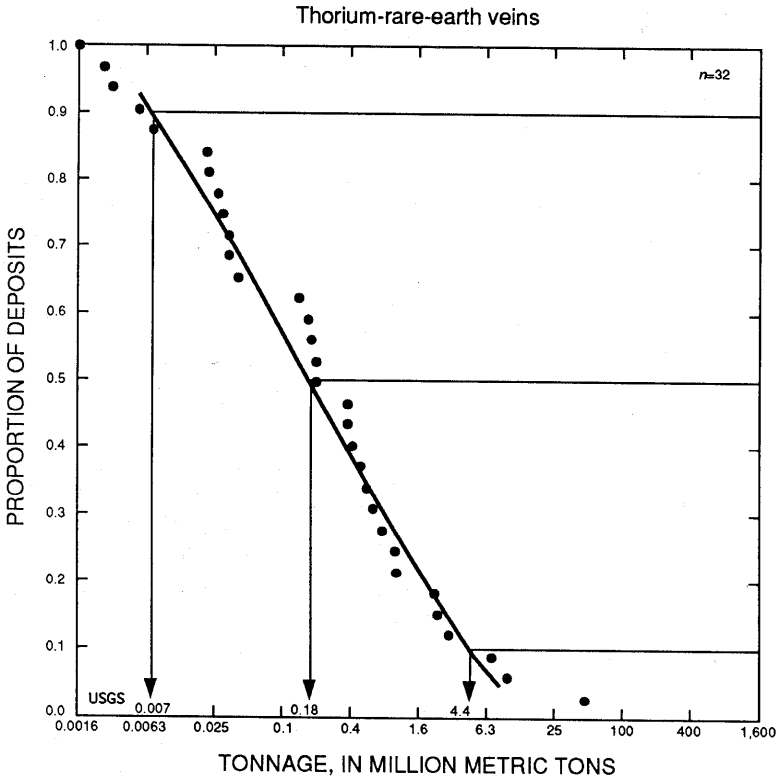

Figure 2. Tonnages of thorium-rare-earth veins.

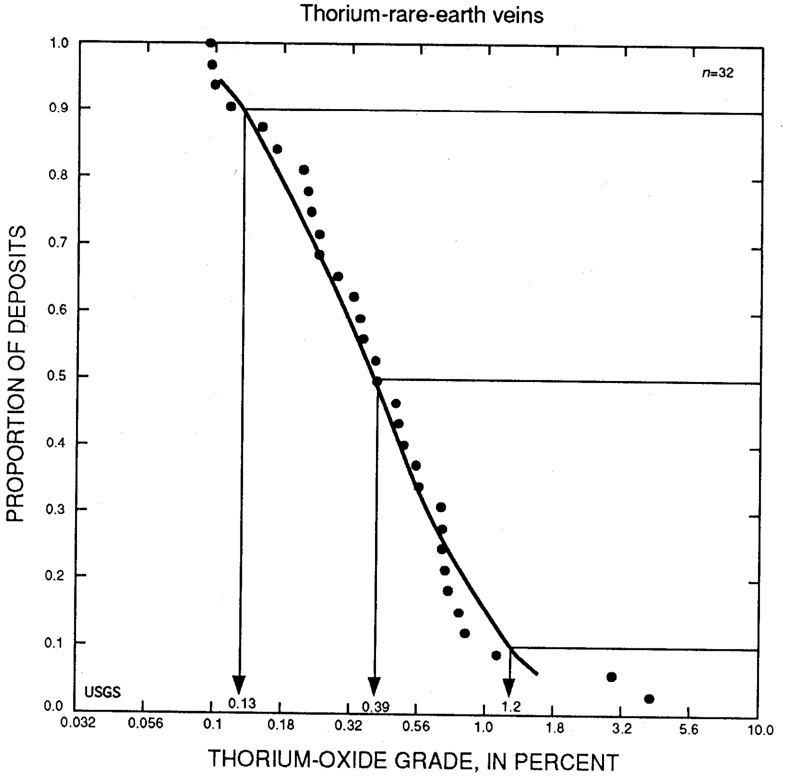

Figure 3. Thorium-oxide grades of thorium-rare-earth veins.

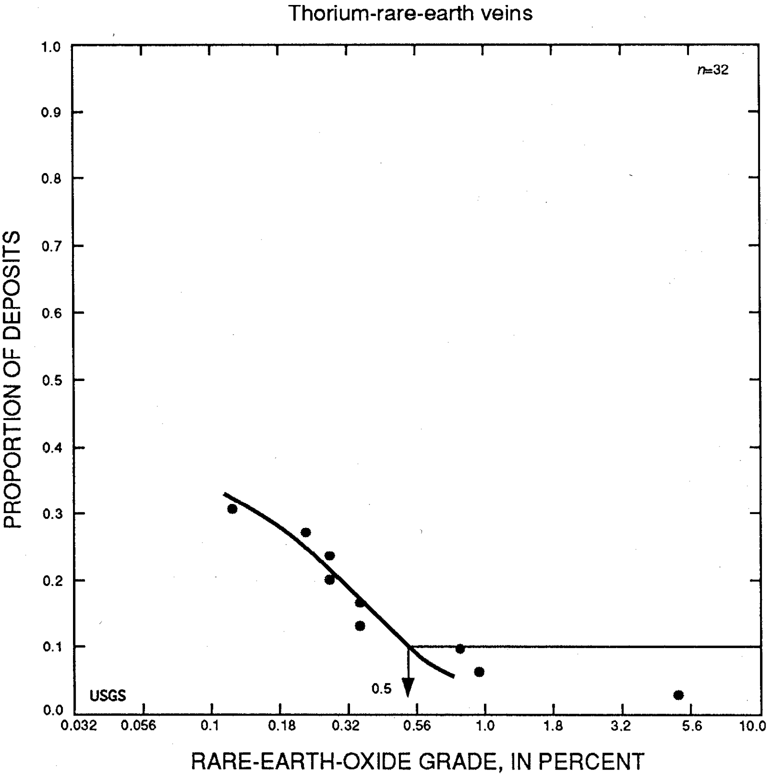

Figure 4. Rare-earth-oxide grades of thorium-rare-earth veins.

DESCRIPTIVE MODEL OF DISTAL DISSEMINATED Ag-Au

By Dennis P. Cox

BRIEF DESCRIPTION

SYNONYM: Sediment-hosted Ag-Au, disseminated Ag

DESCRIPTION: Disseminated Ag and Au mainly in sedimentary rocks distal to porphyry Cu, skarns, and polymetallic veins (Graybeal, 1981).

TYPICAL DEPOSITS: Taylor, Candelaria, Star Pointer, Cove deposits, White Pine district, Nevada; Tecoma, Utah; Vekol, Tombstone, and Hardshell, Arizona.

DISTINGUISHING FEATURES: This model is similar to sediment-hosted Au but has significantly higher Ag grades than that model (see Ag grades in grade and tonnage models for both). It also is characterized by higher geochemical background values

COMMODITIES: Ag, Au

OTHER COMMODITIES: Locally, Sb

ASSOCIATED DEPOSIT TYPES: Porphyry Cu, Cu skarn, Pb-Zn skarn, Au skarn, polymetallic veins, polymetallic replacement and replacement Mn deposits.

REGIONAL GEOLOGIC ATTRIBUTES

TECTONOSTRATIGRAPHIC SETTING: Continental margins.

REGIONAL DEPOSITIONAL ENVIRONMENT: Shelf and basinal sedimentary rocks are folded and faulted and intruded by I-type granitic rocks.

AGE RANGE: Mesozoic-Tertiary in Western United States; may be any age.

LOCAL GEOLOGIC ATTRIBUTES

HOST ROCKS: Carbonate and clastic sedimentary rocks.

ASSOCIATED ROCKS: Felsic hypabyssal or subvolcanic intrusions.

ORE MINERALOGY: Native Au, native Ag, electrum, argentite, Ag sulfosalts, tetrahedrite, stibnite, galena, sphalerite, chalcopyrite, pyrite, marcasite, arsenopyrite; at Cove deposits, stannite and canfieldite.

GANGUE MINERALS: Quartz, rhodochrosite, Ag-rich manganocalcite.

STRUCTURE AND ZONING: Ore minerals sparsely disseminated or in stockwork of thin quartz-sulfide veins.

ORE CONTROLS: Deposits commonly occur in skarn and polymetallic vein and replacement districts outboard of all other types of mineralization. Fracture permeability is the most important ore control. Primary rock permeability may be important locally

STRUCTURAL SETTING: Shear zones, axial plane fractures in folded rocks

ORE DEPOSIT GEOMETRY: Irregular bodies, locally conformable to bedding

ALTERATION: Silicification (Taylor, Star Pointer, Cove) and decalcification (Star Pointer) of carbonate rocks; sericite-clay in clastic rocks (Candelaria).

EFFECT OF WEATHERING: Leaching and redeposition of Ag as cerargyrite forms bonanza deposits (White Pine district, Nevada; Vekol, Arizona).

GEOCHEMICAL SIGNATURES: Ag±Au±Pb±Mn±Zn±Cu±Sb±As±Hg±Te; Mn introduced at Cove, Candelaria, and Star Pointer. Ag:Au ratios are highly variable: Candelaria 400:1; Taylor, 143:1; Tecoma, 60:1; Purísima Concepión, 51:1; Hilltop, <2:1.

GRADE AND TONNAGE MODEL OF DISTAL DISSEMINATED Ag-Au

By Dennis P. Cox and Donald A. Singer

COMMENTS Estimated premining tonnages and grades from the deposits listed in table 5 were used to construct the model. Where several different estimates were available for a deposit, the estimated tonnage associated with lowest cutoff grades was used.

No significant correlations between grades and tonnages were observed. See appendix B for locality abbreviations. See introduction for explanation of the grade and tonnage model as shown in figures 5–7.

Table 5. Grades and tonnages of distal disseminated Ag-Au deposits

[Tonnages in million metric tons; silver (Ag) and gold (Au) grades in grams per metric ton. Country and state abbreviations explained in app. B]

Deposit	Country	Tonnage	Au grade	Ag grade
Candelaria	USNV	27	0.19	50
Cove	USNV	81	1.8	92.5
Fresnillo	MXCO	19	.22	141.6
Hardshell	USAZ	6	0	245
Hilltop	USNV	10.35	2.5	2
Purísima Concepción	PERU	.2	3.1	7.5
Real de Angeles	MXCO	66	0	66.6
Star Pointer	USNV	1.36	4.8	10.3
Taylor	USNV	7	0	103
Tecoma	USUT	1.5	1.56	93.3

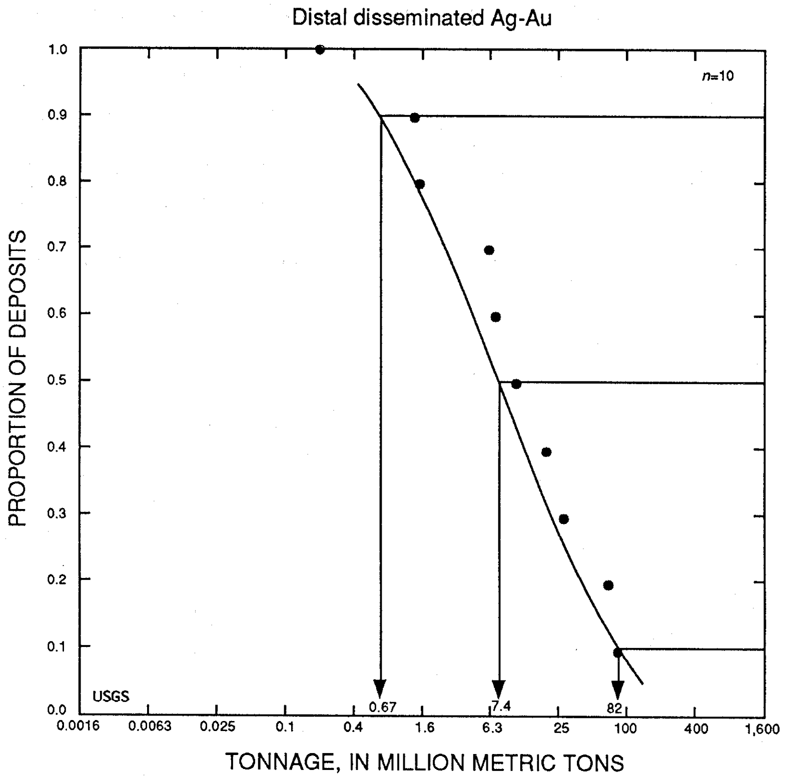

Figure 5. Tonnages of distal disseminated Ag-Au deposits.

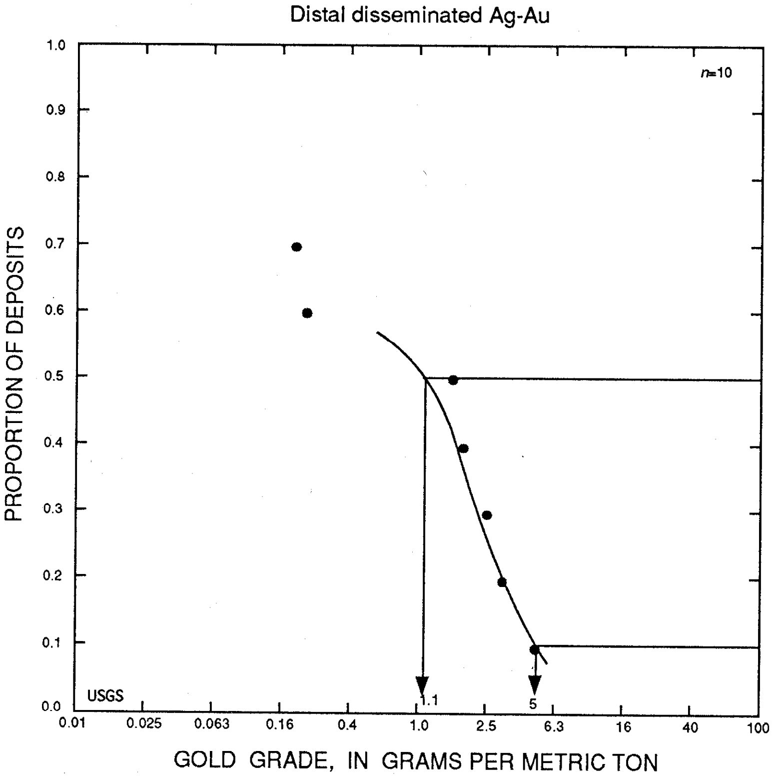

Figure 6. Gold grades of distal disseminated Ag-Au deposits.

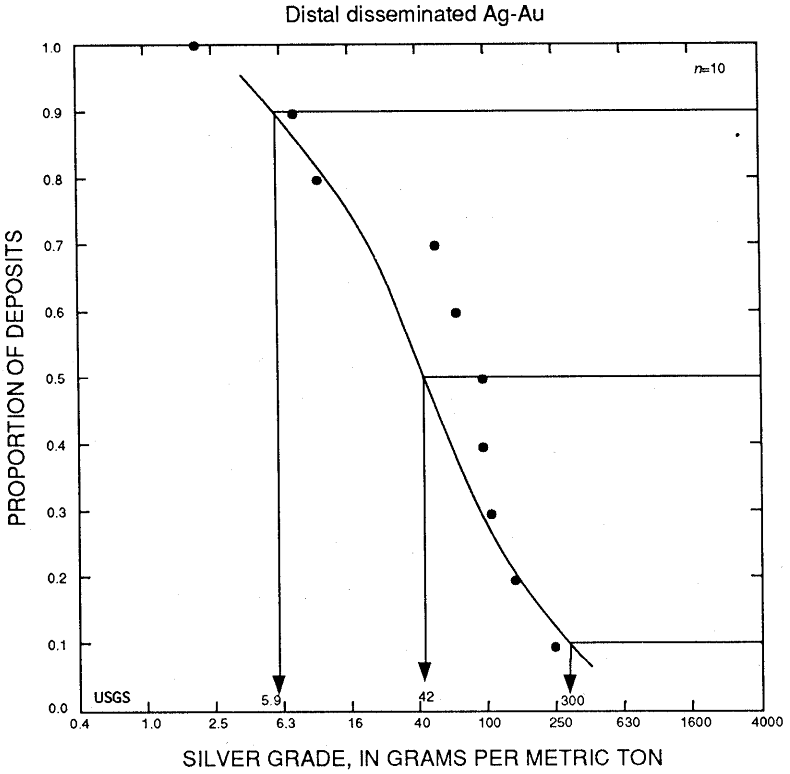

Figure 7. Silver grades of distal disseminated Ag-Au deposits.

Numerical Mineral Deposit Models

By Richard B. McCammon

INTRODUCTION

The numerical mineral deposit models described in this paper are a part of a continuing effort to develop more quantitative approaches to assessing undiscovered mineral resources in graphically defined areas. These models have their origin in the descriptive mineral deposit models of Cox and Singer (1986). As defined by Cox and Singer, descriptive mineral deposit models represent a systematic arrangement of information summarizing the essential attributes (properties) of a class of mineral deposits. Such information is available usually in carrying out regional mineral resource assessments (Shawe, 1981). Descriptive mineral deposit models provide the geologist with a link between deposit types and geologic environments. Establishing links within a given area is the first step of the three-step assessment process described by Singer and Ovenshine (1979). The definition of this step is the delineation of areas according to the types of deposits that the geology will permit.

This decision as to which types of deposits are permitted by the geology of an area is subjective. The decision is dependent almost entirely on the experience of the geologist performing the assessment. The more experienced the geologist, the more likely the models that are selected will be the right ones. Consequently, a team approach involving geologists having knowledge about different deposit models will ensure that a wide range of possibilities will be considered. The best approach is to give the team access to geologists with expert knowledge about the deposit models being considered. The idea of giving the geologist access to experts gave rise to Prospector, an expert system developed during the mid-1970's to aid the geologist in the search for hidden deposits (Duda, 1980). Expert systems are computer programs that achieve competence in performing specialized tasks by reasoning about the task and the task domain (Feigenbaum and others, 1988). During the years of its development, which lasted until 1983, Prospector was regarded as a serious attempt to model the decision-making process involved in the application of deposit models in mineral exploration.

Since 1983, much has changed. Prospector II, the successor to Prospector, has been developed at the U.S. Geological Survey (McCammon, 1989). Two major developments have included (1) the format used to represent deposit models, and (2) the algorithm used to classify mineral occurrences, prospects, and deposits. These developments were necessary in order to (1) acquire a more comprehensive, economical, and adaptable deposit model format, and (2) accommodate changes in the use of descriptive mineral deposit models in regional mineral resource assessments (Singer and Cox, 1988). Numerical mineral deposit models have emerged as a result of these developments.

NUMERICAL MINERAL DEPOSIT MODELS

Numerical models differ from descriptive models in that numerical scores are associated with each model. A maximum score is obtained when the geologist concludes that all of the attributes of a particular model are present. However, maximum scores for different models differ. The reason is that models are made up of different attributes. In particular, two scores—one that is positive, and one that is negative—are associated with each of the attributes. A positive score reflects the degree to which a model is suggested by the presence of a particular attribute. A negative score reflects the degree to which a model is negated when a particular attribute is absent. If, on the other hand, the absence of an attribute is suggestive of a model, a positive score is associated with its absence, and a negative score is associated with its presence. Consequently, the states of presence and absence correspond, respectively, to the conditions of sufficiency and necessity in Prospector (Duda, 1980).

The attributes of numerical models are grouped into headings similar to those of descriptive models. The current headings in the numerical models are the "AgeRange," "RockTypes," "TextureStructure," "Alteration," "Mineralogy," "GeochemicalSignature," "GeophysicalSignature," and "AssociatedDeposits." In an attempt to represent the linkages within these attributes, a taxonomy has been created that facilitates these linkages. For example, under RockTypes, "Granite" is defined as a "kind-of" Felsic-plutonic RockType, which is a "kind-of" Plutonic RockType, which is a "kind-of" Igneous RockType. Thus, numerical models are characterized by generalized attributes as well as by specific attributes. This "kind-of" characterization aids greatly in limiting the number of models considered at any one time. The taxonomy that defines the attributes of the numerical models described in this paper is given in appendix C.

Virtually all of the terms listed in the taxonomy in appendix C appear as attributes in one or more of the descriptive models in Cox and Singer (1986). In creating the numerical models, the decision was made to preserve to the maximum extent possible the terminology used by the authors who contributed the descriptive models. As a result, the taxonomy does not contain terms not found in the descriptive models. Thus, the taxonomy is not a glossary of geology, but rather a glossary of terms used in the descriptive models.

Not all of the headings contained in the descriptive models are included in the numerical models. The reason is that it is not yet possible to define a taxonomy and to assign positive and negative scores for attributes that relate to headings such as "TectonicSetting," "DepositionalEnvironment," and "OreControls". Despite these shortcomings, the numerical models described in this paper offer a further means of quantifying the decision as to which mineral deposit models are permitted by the information collected in regional mineral resource assessments.

WEIGHTING OF THE ATTRIBUTES

The task of assigning positive and negative scores to attributes in the numerical models were aided greatly by the indices prepared by Barton (1986a, b) and Cox (written commm., 1987). The indices contain information on the frequency of occurrence of geochemical anomalies, minerals, and types of alteration according to the descriptive models contained in Cox and Singer (1986). Associated with each attribute was an index number ranging from +5 down through 0 to –5 in a system similar to Prospector (Duda and others, 1977). The numbers represent the commonness or rarity of each attribute. It was the intent to have the numbers 1, 2, 3, 4, and 5 correspond, respectively, to the 0–10, 10–30, 30–70, 70–90, and 90–100 percent frequency relationship between the attribute and the deposits represented by the models. In almost all instances, the numbers assigned were "best" guesses based on experience. In the future, the compilation of such data would make the assignments less subjective. For the numerical models, the attributes were each assigned a positive and negative number for each model according to the levels given in table 1. Negative levels correspond to the frequency of occurrence and express how the absence of an attribute with respect to a particular model is to be weighted. Positive levels express how the presence of an attribute is suggestive of a particular model. For instance, a Leucogranite is highly suggestive (+4) of a Sn-greisen deposit model. The known absence of Felsic-plutonic rocks in an area, however, virtually precludes (–5) the existence of Sn greisen deposits. Generally, the numbers were assigned so that they reflected as near as possible the context in which the attributes were defined by the compilers of each of the models. In the final analysis, however, the assignment is a trial-and-error process.

Table 1. Quantization levels for presence/absence of particular mineral deposit

State	Level	Verbal description
Degree of sufficiency		
	5	Very highly suggestive
	4	Highly suggestive
Presence	3	Moderately suggestive
	2	Mildly suggestive
	1	Weakly suggestive
Degree of necessity		
	–1	Infrequently present
	–2	Occasionally present
Absence	–3	Commonly present
	–4	Most always present
	–5	Virtually always present

In many cases, it was not possible even by trial and error to assign positive and negative numbers to the attributes. A rationale for assigning numbers was simply lacking. In these cases, default numbers of +2 and –2, respectively, were used.

SCORING OF THE ATTRIBUTES

The score that was assigned to an attribute in a numerical model was dependent upon the heading to which it belonged. In reviewing the descriptive models, it was recognized that the number of attributes within a heading varied from one model to the next. Different headings contained a different number of attributes. As a result, it was necessary to devise a weighting scheme that would take this into account. The intent was to balance the scores associated with each heading with the scores assigned to each attribute within each heading. In order to accomplish this, the levels in table 1 were associated with the scores given in table 2. Thus, the score associated with the highest positive (and negative) level for each heading reflects both its relative importance in defining a particular model and the number of attributes it contains. For example, the maximum score for a particular rock type cannot exceed

Table 2. Quantization levels and associated scores for mineral deposit models

[Abbreviations: Age, AgeRange; Rk, RockTypes; Alt, Alteration; Min, Mineralogy; Gx, GeochemicalSignature; Gp, GeophysicalSignature; Dep, AssociatedDeposits. Default levels: 2, presence; –2, absence]

	Presence						Absence				
Level	5	4	3	2	1	0	–1	–2	–3	–4	–5
Age:	100	40	40	40	40	0	–100	–100	–100	–100	–100
Rk:	75	60	45	30	15	0	–5	–10	–45	–60	–75
Alt:	400	300	200	100	50	0	–2	–10	–100	–200	–400
Min:	75	60	45	30	15	0	0	–5	–10	–30	–75
Gx:	75	60	45	30	15	0	0	–5	–10	–30	–75
Gp:	250	150	50	25	10	0	–10	–50	–100	–200	–250
Dep:	400	320	200	150	75	0	–50	–100	–200	–300	–400

75. However, virtually all of the numerical models are characterized by several rock types. Thus, if all types are present, the total score for rock types will be many times 75.

UNCERTAINTY IN THE EVIDENCE

In Prospector, the geologist was asked to state the degree of certainty about the presence or absence of evidence (Duda and others, 1977). The degree of certainty was expressed on a scale from +5 through 0 to –5 for which +5 was taken as absolute certainty about the presence of the evidence and –5 was taken as absolute certainty about the absence of the evidence. A value of 0 was taken to mean indifferent or "don't know." The degree of belief expressed by the geologist was used to adjust the strength of the rules relating to the evidence.

For the numerical models, a simpler method has been devised. For a given model, an attribute is judged as being present, suspected of being present (present?), missing, or absent. Absence is treated as the attribute having been looked for but not found. Missing is treated as the default, meaning that the attribute is neither present or suspected of being present nor known to be absent. If all of the attributes within a heading are missing, a default score of 0 is assigned to the heading. Thus, if no information exists on the known deposits in an area, the heading "AssociatedDeposits" is assigned a 0 score. If only some of the attributes within a heading are missing, the attributes that are missing are assigned the score corresponding to the level of –1. Attributes suspected of being present are assigned the next less positive level than the level associated with their presence. Experience to date indicates that this treatment of uncertainty in the observations is sufficient for taking into account the quality of the information available in regional mineral resource assessments.

The "AgeRange" heading is treated differently from the other headings. A statement that was made for many of the descriptive models in Cox and Singer (1986) was that deposits of the type represented by the model are restricted mainly to one interval of geologic time but may be of any age. In this sense, "AgeRange" is not particularly restrictive for these models. It was decided to assign a single score to the "AgeRange" heading—namely, a score of +100 if any part of the interval specified by the geologist lies within the interval specified by the compiler of the model, a score of –100 if it did not, a score of +40 if the geologist was uncertain about the "AgeRange," and a score of 0 if no information is available. As defined by Singer and Cox (1988), "Age" refers to the age of the event responsible for the formation of the deposit. For many areas, this age is unknown.

"TextureStructure" is not used as a basis for numerical scoring because it describes the morphology of deposits, and morphology is generally not well recognized at the time an assessment is made. If the morphology is known, the geologist tends to focus quickly on those models whose deposits exhibit these characteristics. The attributes within "TextureStructure" serve more as a checklist for identifying the types of deposit models to be considered in any given situation.

WORKSHEETS FOR NUMERICAL MODELS

Worksheets for the numerical mineral deposit models are given in appendix D. The model numbers for the numerical models correspond to the model numbers for the descriptive models in Cox and Singer (1986). The worksheets are designed to be reproduced and used to score geologic descriptions of areas that may contain mineral occurrences, prospects, or deposits. The worksheets can be used to determine numerically the degree to which a given geologic description matches a particular model. If, after scoring, there is doubt about the choice of a particular model, reference can always be made to the original model contained in Cox and Singer (1986).

A WORKED EXAMPLE

To illustrate how a person might fill in a worksheet, the following example is taken from field observations and subsequent thin-section studies and geochemical analyses of a massive, quartz-rich, seriate to porphyritic Tertiary granite that occurs in the White Mountains of east-central Alaska (Weber and others, 1988). An earlier investigation (Dean Warner, written commun., 1984) suggested that the granite might be a host for Sn greisen deposits. With this in mind, the worksheet for the Sn greisen deposit model was filled in using the scores in table 2 based on the information that was available. The worksheet along with the scores of the attributes, is shown in table 3.

In the example, the age of the granite was established to be Tertiary and was considered to be the age of any mineralization that may have occurred. As a Tertiary age falls within the Phanerozoic age interval, a score of 100 is assigned to Phanerozoic on the worksheet.

Muscovite-leucogranite was identified as the major rock type present. On the worksheet, Muscovite-leucogranite is assigned a level of 3 for presence. Referring to table 2, the score that is associated with a level of 3 for RockTypes (Rk) is 45. Therefore, the score for Muscovite-leucogranite is 45. Taking note that Muscovite-leucogranite is a kind-of Leucogranite, Leucogranite is also present therefore. On the worksheet, Leucogranite is assigned a level of 4 for presence. Referring to table 2, the score that is associated with a level of 4 for Rk is 60, and therefore the score assigned to Leucogranite on the worksheet is 60. By similar reasoning, Granite and Felsic-plutonic RockTypes are also present, and by referring to table 2, they are each assigned the score of 75. The remaining RockType (Biotite-leucogranite) was missing—that is, neither its presence nor its absence could be confirmed. On the worksheet, Biotite-leucogranite is assigned a level of –2 for absence. As Biotite-leucogranite is considered missing rather than being absent, referring to table 2, the score associated with one level higher—that is, a level of –1—is –5, and therefore the score assigned to Biotite-leucogranite on the worksheet is –5.

In a similar way, scores were assigned to the remaining attributes under the different headings on the worksheet. Under each heading, the score assigned to each attribute was based on the score associated with the level specified for the attribute depending on whether the attribute was judged to be present, suspected to be present (present?), missing, or absent. Attributes whose presence-absence levels were not specified were assumed to be 2 and –2, respectively. Under headings for which there was no information available, (AssociatedDeposits, for instance, in this example), the score assigned to all of the attributes was 0.

When scores for all of the attributes were assigned, the partial scores—that is, the total scores under each heading—were calculated.

The total score in this example was 1,055 out of a possible maximum score of 2,930. Although this score is relatively low compared with the maximum score, scores for the four next highest scores among all of the other models obtained using Prospector II were 637 out of 2,430 for Sn veins, 576 out of 2,445 for Climax Mo, 559 out of 1,730 for Porphyry Sn, and 466 out of 1,795 for W veins. It should be noted that absolute rather than relative scores are used for ranking purposes. It was concluded that even though this area could not be considered a likely prospect for Sn greisen deposits, if deposits should exist, they most likely would be of this type rather than any other type.

This example brings out a problem that has persisted throughout the development of the models: the continuing confusion between regional and local characteristics. In performing regional mineral resource assessments, the scores obtained in applying the numerical models tend to be low, largely owing to the lack of information. At the same time, application of a particular model in an area in which the information is sufficient to conclude that, in all probability, one or more deposits of the type represented by the model do not exist results in large scores because the model, in detail, is not discriminating enough. Thus, even though such differences in scores that are obtained by application of the models in different areas are probably real and usable, reliance on absolute scores could lead to serious misinterpretation, and for this reason, caution is urged in applying the results indiscriminately.

TEST OF NUMERICAL MODELS

As a test of the numerical models, an experiment was performed that was designed to compare the results of classifying 124 lode deposits in Alaska by a panel of eight geologists using the Cox and Singer (1986) classification with the results obtained by classifying the same deposits using the numerical models. The 124 lode deposits were classified by the panel using the descriptions of the deposits given in Nokleberg and others (1987). Using the same descriptions, the 124 deposits were classified by Prospector II using the numerical models. The results of the experiment are summarized in table 4. The 124 deposits were classified by the panel of geologists into 27 different deposit types using the Cox and Singer classification. The five columns on the right in table 4 record the frequency of the rank order in which each of the 124 deposits was clas-

Table 3. Worksheet for numerical model of Sn greisen deposits

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Model 15c

Worksheet for Numerical Model of Sn greisen deposits

Deposit, Prospect, or Occurrence: Cache Mountain

Location: White Mountains, East-Central Alaska

Description: Quartz-rich seriate porphyritic granite with ubiquitous miarolitic cavities and common occurrence of tourmaline.

AgeRange: Precambrian ___ Phanerozoic 100

RockTypes: Felsic-plutonic (5 -5) 75 Granite (5 -5) 75 Leucogranite (4 -4) 60 Muscovite-leucogranite (3 -2) 45 Biotite-leucogranite (3 -2) -5

TextureStructure: Greisen ____ Veinlets ✓ Stockwork ______

Alteration: Greisenization (5 -2) -10 Albitization (5 -2) -10 Tourmalinization (3 -2) 200

Mineralogy: Cassiterite (4 -5) 60 Molybdenite (4 -5) -75 Arsenopyrite (3 -5) 30 Topaz (4 -2) 60 Tourmaline (4 -2) 60 Beryl (2 -4) 0 Wolframite (2 -3) -10 Bismuthinite (2 -2) -5 Fluorite (4 -3) 60 Calcite (1 -3) 15 Pyrite (2 -4) 30

GeochemicalSignature: Sn (4 -5) 60 F (5 -5) 75 B (5 -4) 75 Mo (2 -5) 0 Rb (2 -4) 0 Cs (2 -4) 0 Be (2 -3) 30 REE (2 -4) -30 U (2 -4) 30 Th (2 -4) 0 Nb (2 -4) 0 Ta (2 -4) 0 Li (2 -4) 0 W (2 -3) 30 As (2 -4) 0 Bi (2 -3) 30

GeophysicalSignature:

AssociatedDeposits: Sn greisen 0 Sn veins 0 Sn replacement 0

MaxScore: 2,930

Partial Scores

AgeRange: 100 **RockTypes:** 250 **TextureStructure:** 0 **Alteration:** 180

Mineralogy: 225 **GeochemicalSignature:** 300 **GeophysicalSignature:** 0

AssociatedDeposits: 0

Model Score: 1,055

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sified using the numerical models. For example, of the six deposits classified by the panel as being a Gabbroic Ni-Cu deposit type, four of these were also classified as being a Gabbroic Ni-Cu deposit type by Prospector II. For the other two deposits, however, a Gabbroic Ni-Cu deposit type was Prospector II's third choice for one and fifth choice for the other. It should be noted that for both of these deposits, the panel had a question mark after their choice.

Table 4. Comparison of classification between Prospector II and panel of geologists using the Cox-Singer deposit classification for 124 metalliferous lode deposits in Alaska (Nokleberg and others, 1987)

[Alphanumeric characters in parentheses refer to model numbers in Cox and Singer (1986)]

Deposit type (classified by panel of geologists)	Frequency of ranking (classified by Prospector II) 1st	2nd	3rd	4th	5th
1. Gabbroic Ni-Cu deposits (7a)	4	0	1	0	1
2. Podiform chromite deposits (8a)	7	1	0	0	0
3. Serpentine-hosted asbestos deposits (8d)	1	0	0	0	0
4. Alaskan-PGE (9)	5	0	0	0	0
5. W skarn deposits (14a)	1	0	0	0	0
6. Sn skarn deposits (14b)	2	0	0	0	0
7. Sn vein deposits (15b)	1	0	1	0	0
8. Sn greisen deposis (15c)	1	0	0	0	0
9. Porphyry Cu deposits (17)	4	1	0	0	0
10. Cu skarn deposits (18b)	2	0	1	0	0
11. Zn-Pb skarn deposits (18c)	2	0	0	0	0
12. Fe skarn deposits (18d)	4	1	0	0	0
13. Porphyry Cu-Mo deposits (21a)	1	0	2	0	0
14. Porphyry Mo, low F deposits (21b)	1	0	0	0	0
15. Polymetallic vein deposits (22c)	14	3	0	0	0
16. Basaltic Cu deposits (23)	0	0	1	0	0
17. Cyprus massive sulfide deposits (24a)	0	0	1	0	0
18. Besshi massive sulfide deposits (24b)	3	0	0	0	0
19. Epithermal vein deposits (25b, 25c, 25d, 25e)	2	0	0	0	0
20. Hot-spring Hg deposits (27a)	3	1	0	0	0
21. Sb-Au vein deposits (27d, 27e)	5	0	0	0	0
22. Kuroko massive sulfide deposits (28a)	9	0	0	0	0
23. Sandstone U deposits (30c)	1	0	0	0	0
24. Sedimentary exhalative Zn-Pb deposits (31a)	2	0	0	0	0
25. Bedded barite deposits (31b)	2	0	0	0	0
26. Kipushi Cu-Pb-Zn deposits (32c)	1	0	0	0	0
27. Low-sulfide Au quartz vein deposits (36a)	25	1	0	0	0
Totals	103	8	7	0	1

Of the 124 deposits classified by the panel, 103 of these were classified the same by Prospector II. This represents an 83 percent agreement between the two sets of classifications. The deposit types for which there was perfect agreement between the two were Serpentine-hosted asbestos, Alaskan-PGE, W skarn, Sn skarn, Sn greisen, Zn-Pb skarn, Porphyry Mo–low F, Besshi massive sulfide, Epithermal vein, Sb-Au vein, Kuroko massive sulfide, Sandstone U, Sedimentary exhalative Zn-Pb, Bedded barite, and Kipushi Cu-Pb-Zn. In almost all cases, the deposit type receiving the highest score was clearly distinguishable from the other deposit types, which received considerably lower scores. There were 8 deposits for which the classification made by the panel was Prospector II's second choice. For 5 of these deposits, the panel either put a question mark after their choice or else suggested that the deposit could be considered one of two different deposit types. Such ambiguity highlights the fact that the classification of a deposit often is largely a matter of judgment. The scores obtained using Prospector II for each of the 9 deposits characteristically were not markedly different for the first and second choices. By combining Prospector II's first and second choices as indicating a match with the classification made by the panel, there was agreement in 111 out of the 119 deposits classified—that is, a 93 percent agreement.

The deposit for which there was the most disagreement between the panel and Prospector II was the Spirit Mountain deposit (Nokleberg and others, 1987, p. 87). The panel classified this deposit as a Gabbroic Ni-Cu deposit type with a question mark, whereas Prospector II classified the deposit unequivocally as a Dunitic Ni-Cu deposit type (Cox and Singer, 1986, p. 24). The deposit is described as disseminations of sulfides in serpentinized peridotite and pyroxenite that are associated with gabbroic sills that have intruded upper Paleozoic limestones. The ore minerals contain Ni and Cu. This description fits closely with the Dunitic Ni-Cu deposit model described as disseminated sulfide mineralization in intrusive dunites and olivine peridotites that exhibit prograde and retrograde serpentinization. Although the description of the Gabbroic Ni-Cu deposit model is similar, what is lacking in the model is any mention of serpentinization. This attribute was critical in this instance. The three other deposit models that Prospector II rated higher than the Gabbroic Ni-Cu deposit model were the Alaskan-PGE, Podiform chromite, and Serpentine-hosted asbestos deposit models. In order to resolve all the differences in the classification of this particular deposit, it would be necessary to review the description again with the panel members and compare it with the descriptions of these five models.

A different situation exists for the Bernard Mountain deposit (Nokleberg and others, 1987, p. 55), in which the panel members classified the deposit as a Podiform chromite deposit type, whereas Prospector II narrowly classified the deposit as a Bushveld-Cr deposit type. The score for the Bushveld-Cr deposit model was 380 out of a possible 1,705, whereas the score for the Podiform chromite deposit model was 360 out of a possible 1,325. Situated in between these two models, were the scores for the Alaskan-PGE and the Merensky-Reef-PGE deposit models, which were 370 out of a possible 1,925 and 365 out of a possible 1,750, respectively. The relatively low scores obtained for all four of the models suggest that it may not be possible with the present information to distinguish among them.

CONCLUSIONS

Numerical mineral deposit models demonstrate the technical feasibility of encoding descriptive mineral deposit models to provide (1) a numerical-based consultant for regional mineral resource assessments, (2) objective evaluations of particular geologic settings as part of regional assessments, and (3) determination of the most likely model or models that best match a particular geologic setting. This approach is potentially valuable for (1) screening data bases of mineral occurrences, (2) providing instruction about the geology of mineral deposits, (3) systematizing the development of mineral deposit models, and (4) introducing objective procedures for evaluating models numerically.

While these numerical deposit models have useful applications in their present form, the extent to which their potential can be realized will depend upon future activities, some of which are already in progress. First, it is clear that the numerical models cannot be better than the descriptive models upon which they are based. The 87 numerical models represent but a sampling of what is ultimately desirable. Moreover, only a few of the numerical models have been completely tested and calibrated for regional mineral resource assessments. Many years will be required to develop numerical models for all types of deposits of economic interest, and refining these models and introducing new models as new deposit types are identified will be a continuing task. Fortunately, the formats that have been developed for the descriptive models will make it easier to carry out this task.

Because the techniques used to develop numerical models are new, few geologists are familiar with them. As the advantages of this numerical approach become more widely appreciated, more geologists will be interested in becoming involved in this activity. Several activities could encourage their participation, including (1) further exposure of these ideas at professional conferences and workshops, (2) acceptance of the publication of such models as a significant professional activity, (3) incorporation of these ideas in a course on economic geology, and (4) provision of ways for geologists in the governmental, academic, and industrial communities to access the models by computer.